Lunar Calibration:
Using the Moon as a Calibration Source for Earth-Observing Instruments in Orbit

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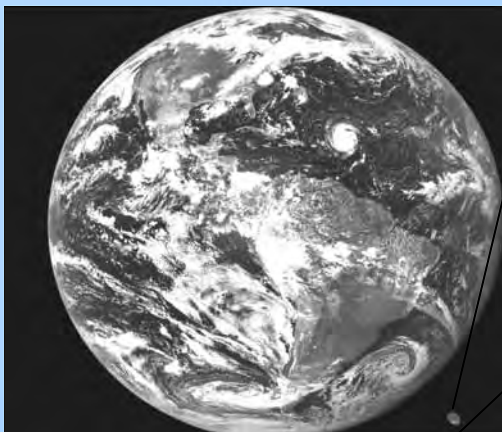
Outline

- The Moon as a radiometric source
  - USGS lunar calibration program
- Current capabilities of lunar calibration
- Ongoing development, needs
- Future improvements: LUSI proposal

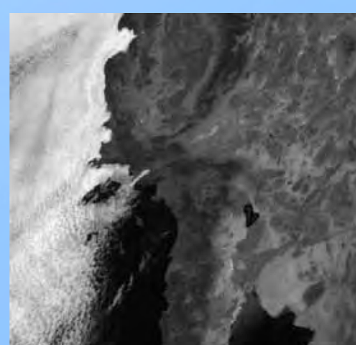
The Moon as a radiometric source

- Available – accessible to all spacecraft in Earth orbit
- Surface reflectance is stable to $<10^{-8}$ per year[1]
- Dynamic range similar to that of clear land

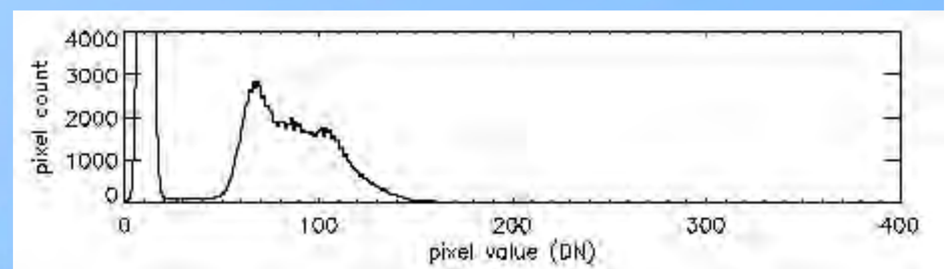
Extracts from GOES full-disk image:



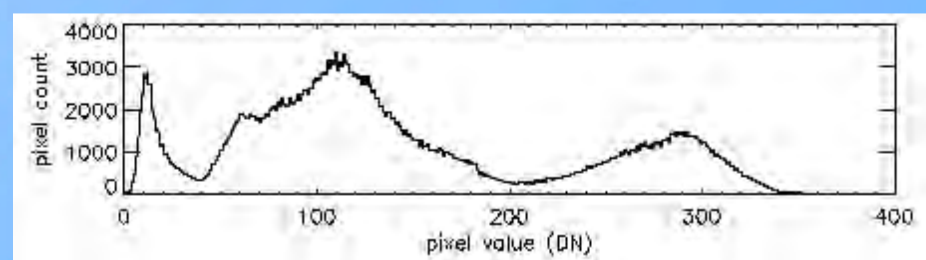
GOES-12 vis channel
2004 August 30 17:45:14



space Moon



ocean land cloud



[1] Icarus 130, 323-327 (1997)

The Moon as a radiometric source

- Brightness is highly variable with geometry
  - phase, spatial non-uniformity, lunar librations, complex reflectance function

This variability mandates using a photometric model for calibration uses.

- Need to accommodate the geometry of illumination and viewing for a spacecraft lunar observation without restriction
- The stability of the lunar surface reflectance means that a model, once established, can be applied to observations made at any time
- In order to capture the lunar radiometric behavior sufficiently for modeling, a multiple-year database of measurements is required

The NASA-funded lunar calibration program at USGS has focused primarily on modeling the quantity of spatially-integrated lunar irradiance.

- Model basis is a dataset of lunar radiance measurements (images) acquired by the ground-based RObotic Lunar Observatory (ROLO)

ROLO observational program

Dedicated observatory, located at USGS in Flagstaff, AZ

Altitude 2143 m

- Dual telescopes
  - –23 VNIR bands, 350-950 nm
  - –9 SWIR bands, 950-2500 nm

- Spatially resolved radiance images
  - 6+ years in operation, >85000 lunar images
  - Coverage in phase from eclipse to 90°, all librations viewable from Flagstaff
  - >800,000 star images, for nightly atmospheric extinction corrections

USGS lunar irradiance model

Model inputs for fitting are developed from images calibrated to exoatmospheric radiance, spatially integrated to irradiance $\boldsymbol{I}$, and converted to reflectance $\boldsymbol{A}_k$:

$$I_k = A_k \cdot \Omega_M E_k / \pi$$

E_k = Solar spectral irradiance
$\Omega_M = 6.4236 \times 10^{-5}$ sr

Empirical model form, for band k **:**

$$\ln A_k = \sum_{i=0}^{3} a_{ik} g^i + \sum_{j=1}^{3} b_{jk} \Phi^{2j-1} + c_1\theta + c_2\phi + c_3\Phi\theta + c_4\Phi\phi$$
$$+ d_{1k} e^{-g/p_1} + d_{2k} e^{-g/p_2} + d_{3k} \cos((g - p_3)/p_4)$$

g = phase angle
θ = observer selenographic latitude
ϕ = observer selenographic longitude
Φ = selenographic longitude of the Sun

Ref.: Astronomical Journal 129, 2887-2901 (2005 June)

USGS lunar irradiance model

- 18 coefficients for each ROLO band, 8 are constant across all bands
- ~ 1200 observations fitted for each band
- Mean absolute fit residual over all 32 bands is 0.0096 in ln A, ~1%

This is a measure of the model's capability to predict the lunar irradiance over the full range of phase and libration angles covered

Comparison of lunar irradiance measurements made by an instrument involves a maximum uncertainty due to the model geometric precision ~1%

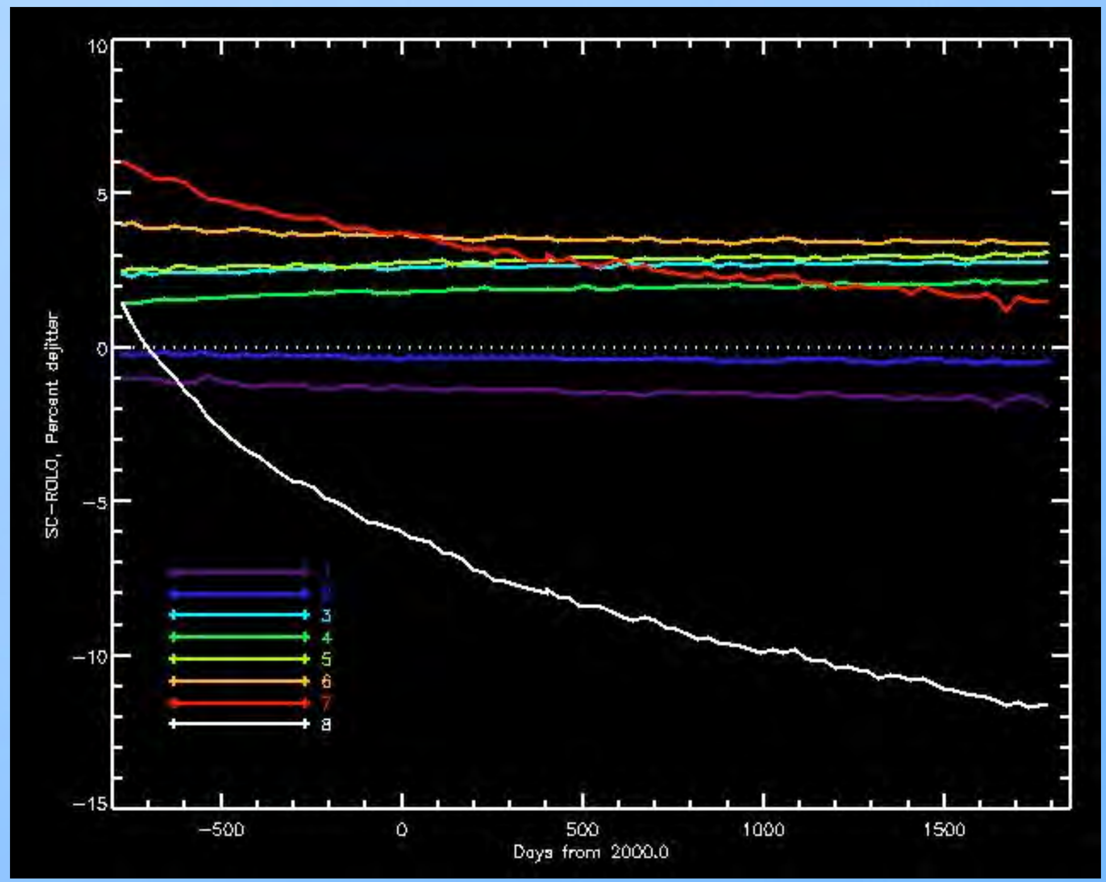
- for any geometry of illumination and viewing (phase and libration)
- restriction to narrow range of phase angles is <u>not</u> a requirement for lunar calibration

Current capabilities — sensor stability monitoring

Given a time series of lunar views acquired by a spacecraft instrument, relative response trending with sub-percent precision can be achieved.

Example: SeaWiFS

- plot is 85 lunar observations (SeaWiFS now has over 160)
- ordinate is discrepancy: [inst/ model – 1.] × 100%
- the lunar comparisons show sensor response degradations of ~5% in band 7 and ~13% in band 8

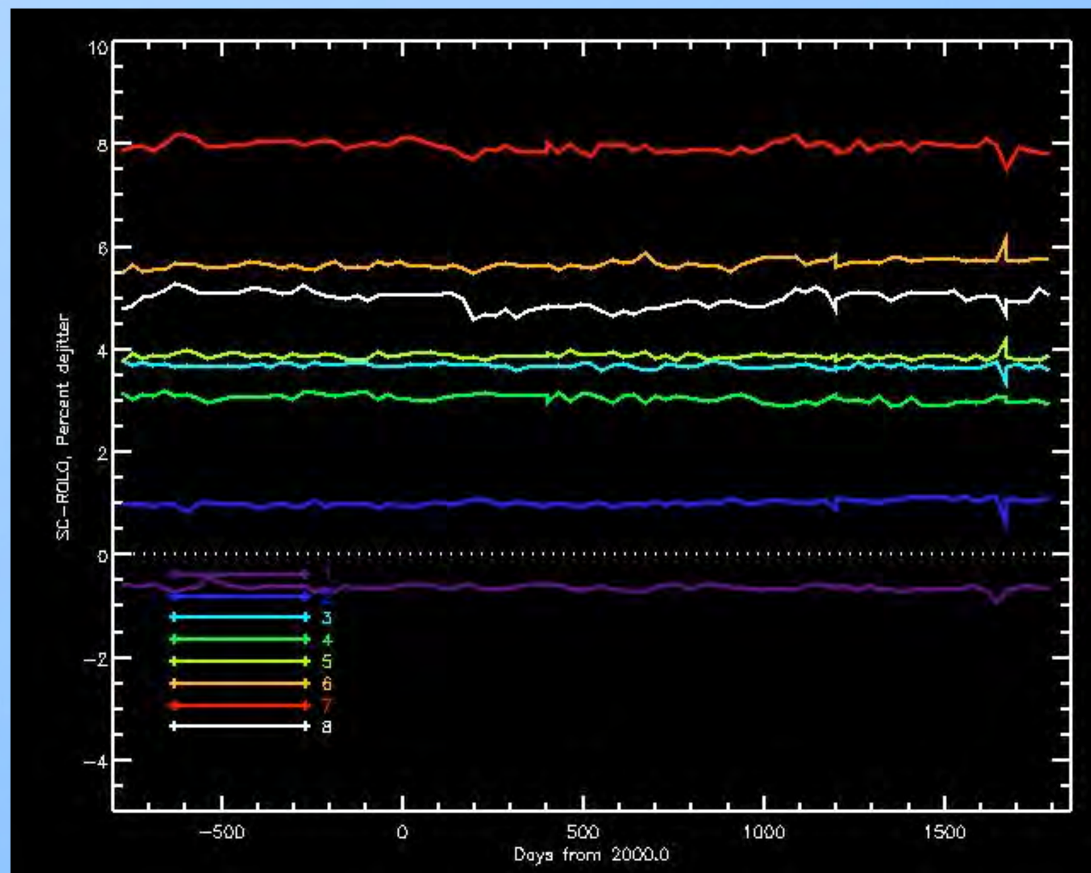


SeaWiFS lunar image, ~6×20 pixels

After correction for sensor degradation based on lunar views, residual SeaWiFS band response trends are < 0.1% per year[1]

This meets the stability requirement for visible-wavelength radiometer measurements of environment variables for climate change

- 85 SeaWiFS lunar observations
- asymptotic temporal correction applied for each band
- distribution of the individual band plots is the difference in absolute scale between SeaWiFS and the lunar model



[1]Applied Optics 43 (31), 5838-5854 (2004)

Lunar model development — absolute radiometric scale

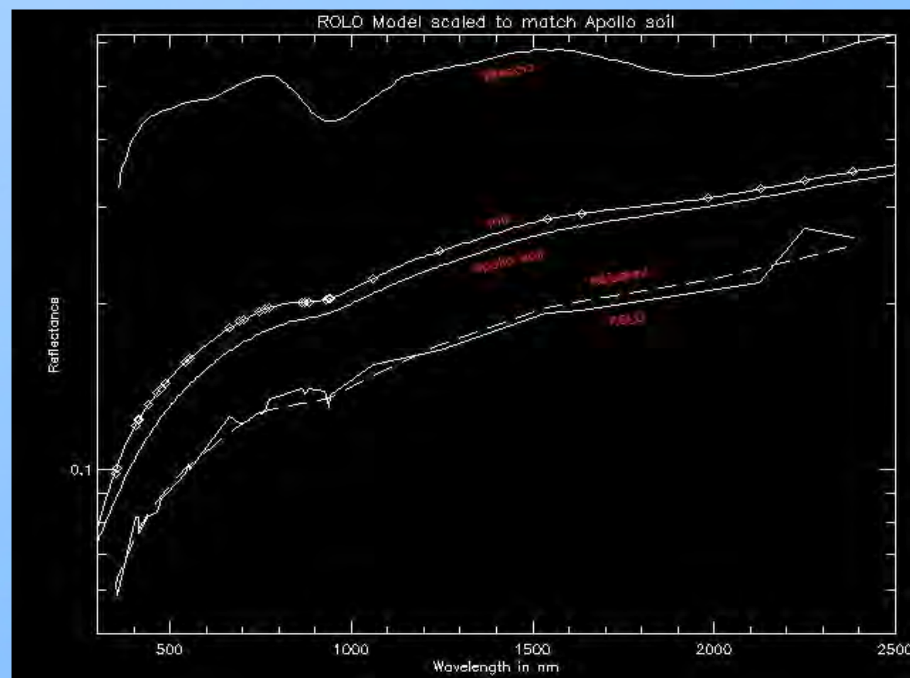
- Current absolute scale is based on observations of the star Vega
  - Uncertainty in Vega absolute photon flux (astronomical measurements)
- Uncertainty in the lunar model absolute irradiance is 5–10%
  - Significantly exceeds model relative precision
  - Based on comparison with calibrated sources, e.g. field calibration at ROLO in collaboration with NIST, NASA, Univ. Arizona

On-axis collimated source at ROLO
• calibrated at NIST

Lunar calibration — applications for the climate mission

- On-orbit sensor stability monitoring
  - Current model capability (precision) can achieve climate requirement
- Instrument cross-calibration and continuity of observational datasets
  - Current cross-calibration capability is 1–3%, dependent on wavelength*
  - For non-overlapping datasets, SI-traceable absolute scale is needed
  - <u>Instruments must view the Moon</u>

*The lunar irradiance model operates in reflectance, which is smooth.



Lunar calibration — challenges in the IR

Possibility has been studied, significant challenges identified

- Temperature range of the sunlit lunar surface ~320–390K
  - 1–2 orders of magnitude larger than typical Earth upwelling radiance
  - 70–80K variations across the surface, requires precise targeting
  - Small-scale, ~5K surface features, requires detailed modeling
- Thermal behavior over the day–night transition must be understood
- Difficulty in acquiring measurements, sufficient number for modeling

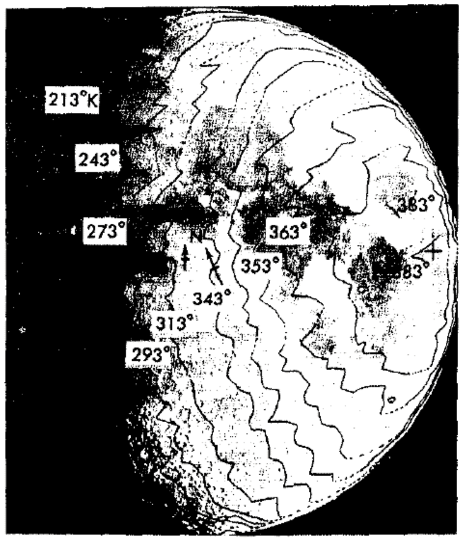


Figure 7. Isothermal contours of 10 November 1959, start 2:17, end 5:23 UT, 63 scans, 0.77 illuminated plotted on a simultaneous photograph after Sinton.[10]

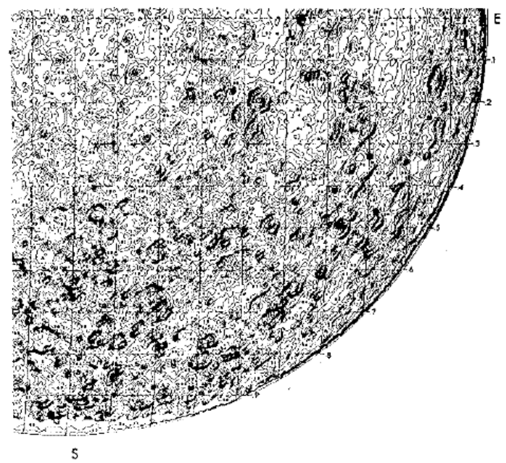


Figure 8. Isothermal contours for the IV quadrant of the full moon (g = ~ 2°16'). The contour interval near the center of the moon is 1.2 K.

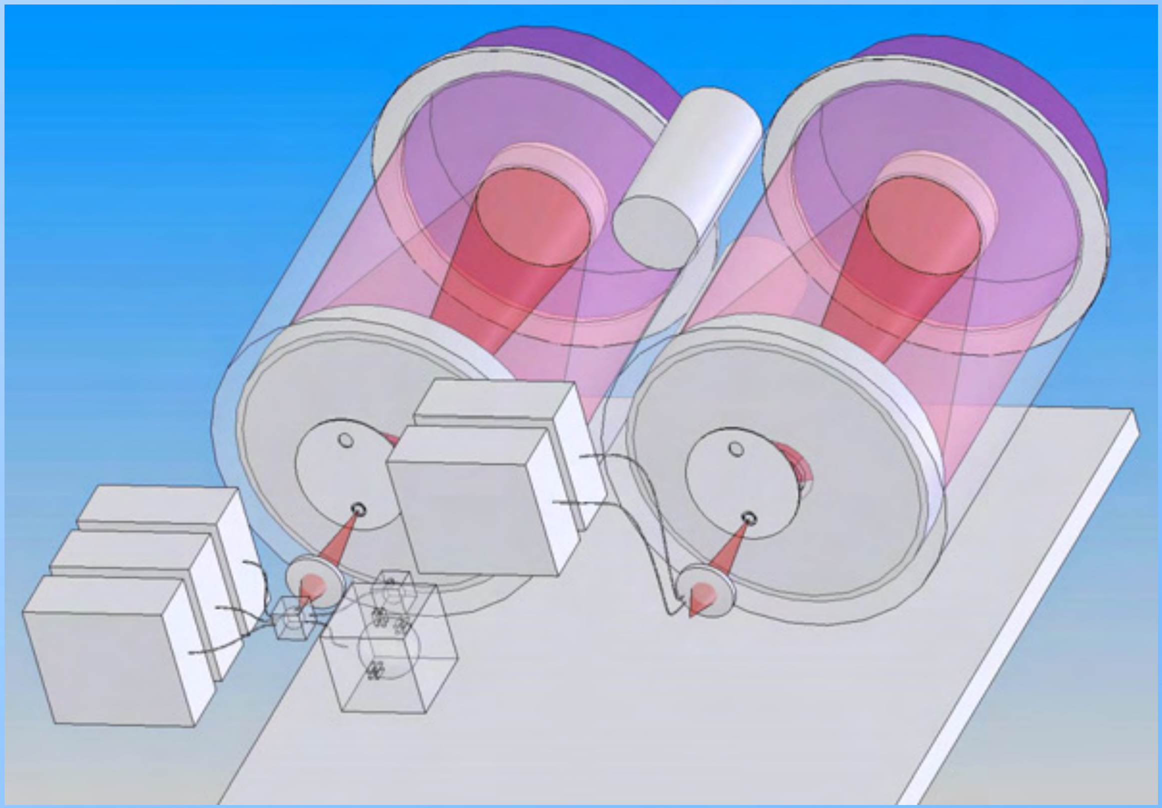
Shorthill, R.W. (1969)
The Infrared Moon

Future improvements — LUnar Spectral Irradiance (LUSI) proposal

- Based with NIST, collaboration with SDL, USGS, Univ. Hawai'i
- Goal to establish the lunar spectral irradiance to <1% absolute (k=1) with direct tie to NIST radiometric standards
- Hyperspectral coverage, 320–2500 nm, spectral resolution 1–4 nm
- Ground-based component — mountaintop observatory site
  - Focus on atmospheric window spectral regions
  - Continuous on-site instrument calibration and characterization
  - Ideal site: Mauna Kea, 4 km altitude
- Flight component — high-altitude balloon (or SOFIA, or ??)
  - Extend spectral coverage to full range
  - Minimize atmospheric effects
  - Instrument calibration at NIST before and after flight

LUSI instrumentation

Twin telescopes, 25.4 cm (10”) f/4 Cassegrain design



Lunar telescope
- non-imaging system — feeds integrating sphere
- 3 fiber-optic coupled spectrographs
- on-board calibration source

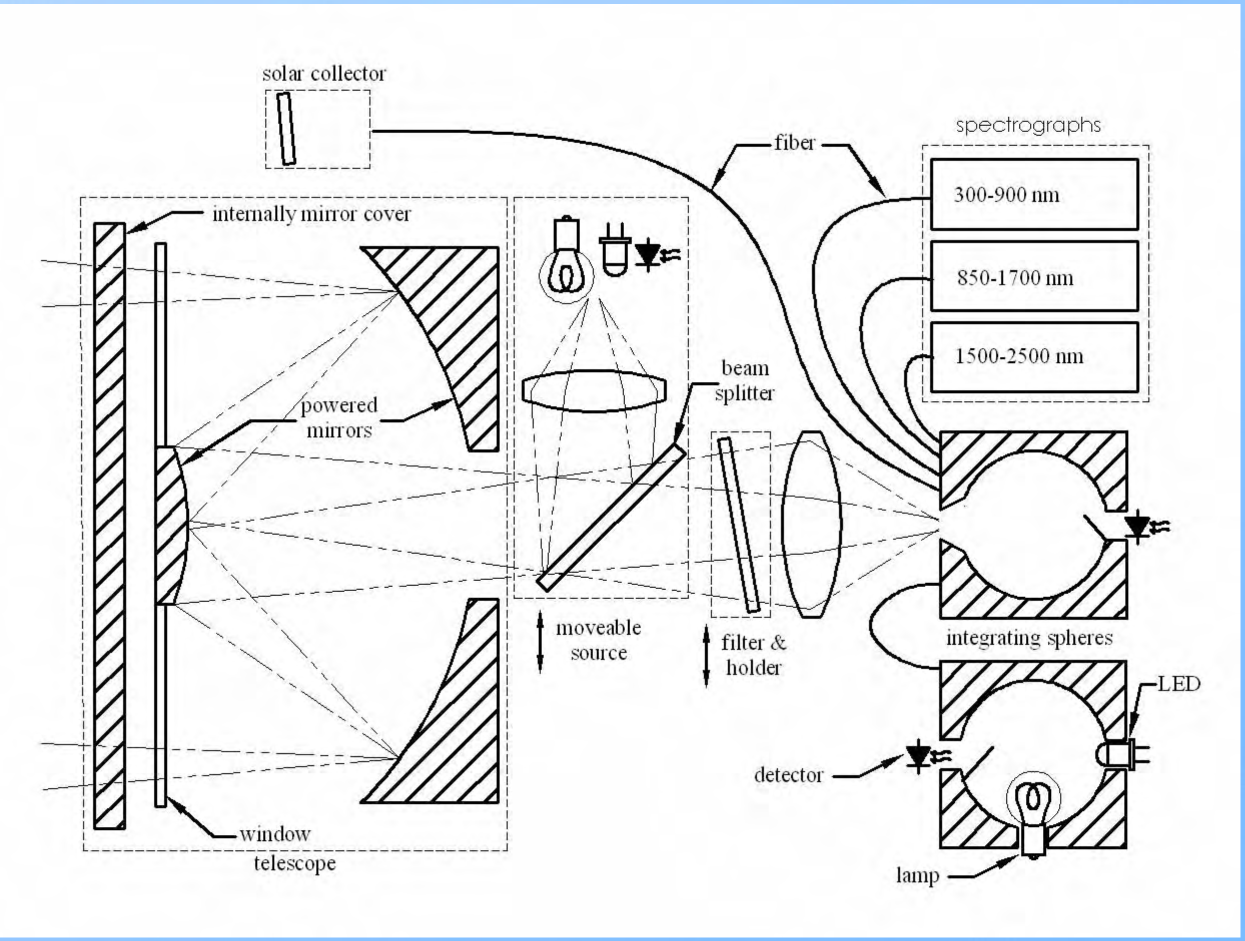
Stellar telescope
- direct feed to fiber-optic coupled spectrographs (2)

Emphasis on stability
- sealed optics with dry N_2 purge
- minimal moving parts
- temperature-controlled environment

LUSI instrumentation — lunar system optical layout

Lunar Spectrographs

- f/3 concave flat-field gratings
- 300 – 900 nm, 1024 Si photodiode array 1 nm bandpass
- 850 – 1700 nm, 1024 InGaAs photodiode array, 2 nm bandpass
- 1500 – 2400 nm, 1024 InGaAs photodiode array, 4 nm bandpass



LUSI instrumentation — calibration and characterization

- Complete instrument characterization at NIST
  - SIRCUS facility, direct tie to primary standards
  - Transfer scale to lunar instrument using detector-based methods
  - System-level testing to validate uncertainty goals
- On-site performance monitoring
  - Multi-wavelength LEDs and lamp, with reference detectors, fiber coupled to collection sphere
  - Deployable autocollimating source to measure system throughput
  - Periodic site visits with NIST field calibration facilities

Atmospheric correction expected to dominate uncertainty budget

Summary

- On-orbit sensor response trending with the precision needed for climate-quality measurements is achievable now
- The Moon can provide a common target for cross-calibration of solar-band instruments and consistency of datasets to develop climate records; the instruments must view the Moon
- Improvement is needed in the absolute accuracy of lunar irradiance and traceability to SI radiometric standards
- Lunar calibration supports the CLARREO strategy of testing and verification against independent calibration methods

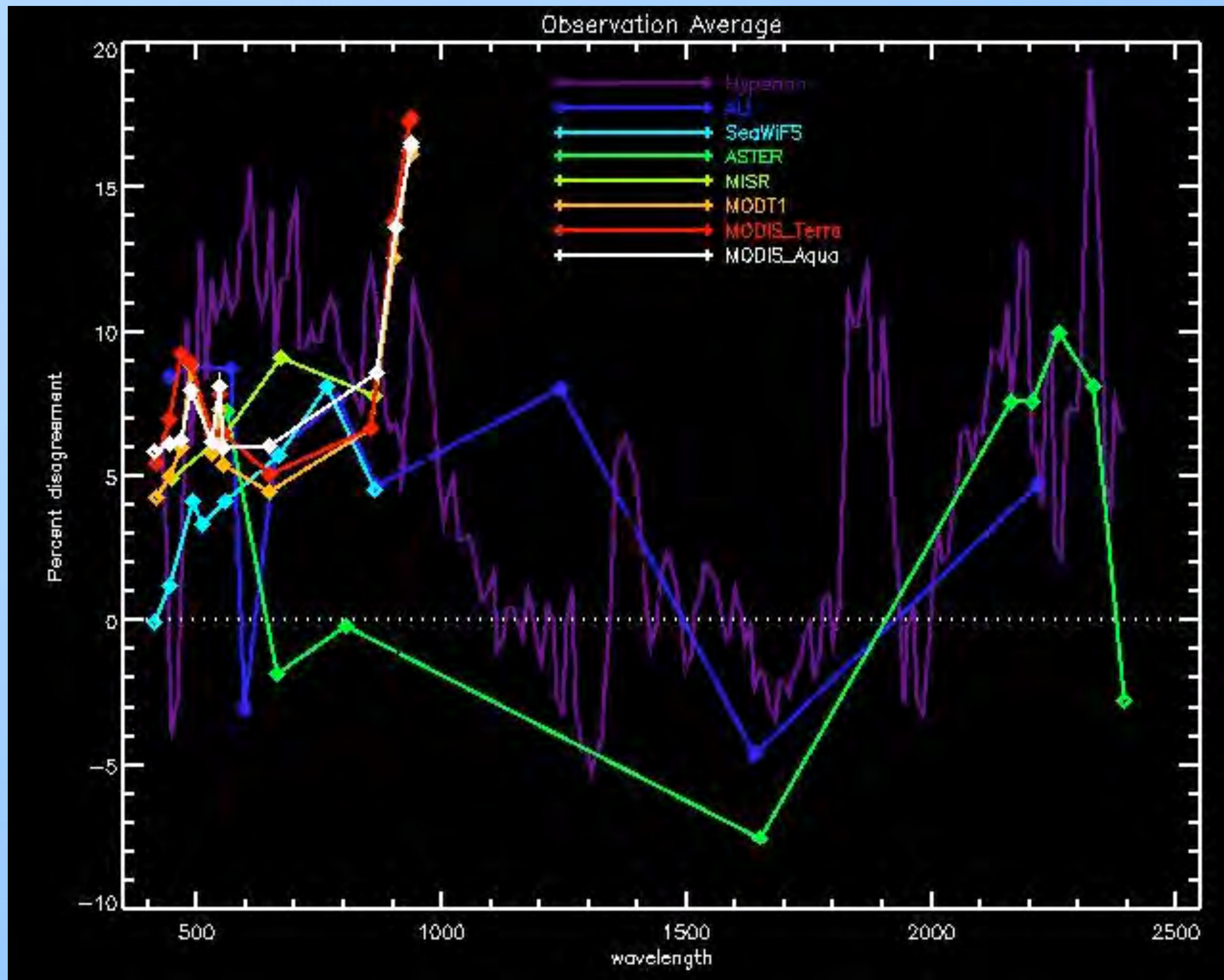
USGS lunar calibration project website:

www.moon-cal.org

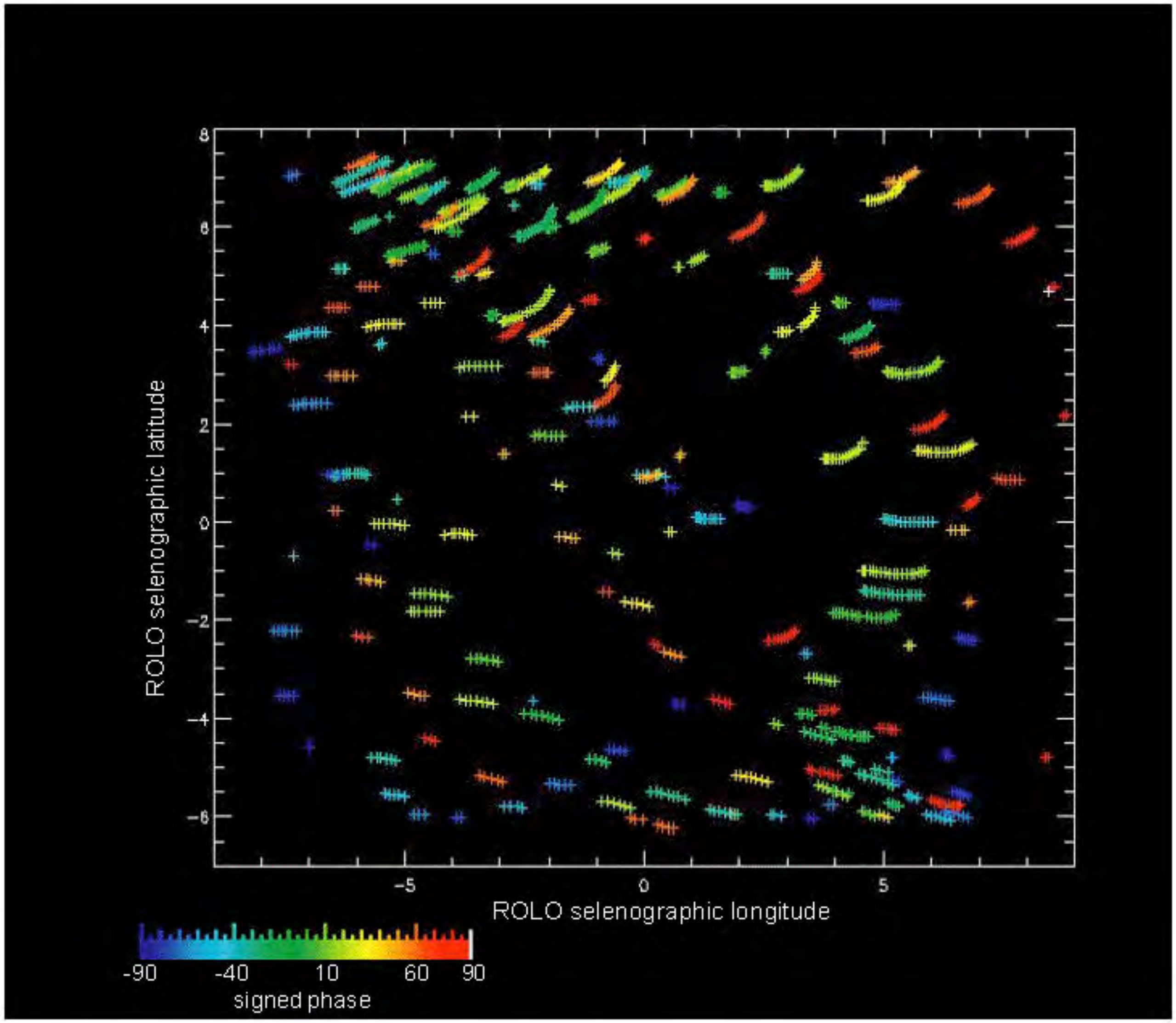
Lunar calibration comparison of EOS instruments

- average of all observations for each instrument

- differences between instruments represent current best practices



ROLO database phase/libration coverage



Lunar irradiance phase function – model and data